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Evidence for short-range correlations in ^{16}O

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Abstract

The reaction $^{16}\text{O}(e,e'pp)^{14}\text{C}$ has been investigated at three values of the transferred energy ω . The differential cross sections were determined as a function of the missing energy and the missing momentum. Evidence for short-range correlations in ^{16}O has been obtained from the transition to the ground state of ^{14}C . The cross sections for this transition are well reproduced by two independent parameter-free microscopic calculations. The results of both calculations show that the reaction is dominated by knockout of a proton pair in a 1S_0 state, driven by short-range-correlations. © 2000 Published by Elsevier Science B.V. All rights reserved.

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1. Introduction

Recently, it was shown that the two-proton knockout reaction $(e,e'pp)$ is a suitable probe for

studying short-range correlations (SRC) in nuclei [1–3]. A comparison of the cross sections measured for the reaction $^{16}\text{O}(e,e'pp)^{14}\text{C}$ with the results of calculations, performed within a factorization approximation of the cross section, led to the conclusion that direct knockout of two protons in a 1S_0 state dominates the reaction [1]. In Ref. [4], the measured

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cross sections were compared to microscopic calculations performed by Giusti et al. [5]. In particular, the data for the transition to the ground state are well reproduced by the calculations. A similar result was obtained by Rosner et al. [6], who investigated the reaction $^{16}\text{O}(e, e'pp)^{14}\text{C}$ at comparable energy and momentum transfer, but different kinematical conditions for the ejectiles. Both studies provided clear signatures for a reaction driven by SRC, but other competing processes are known to contribute to the cross section as well. In particular, a sizeable contribution from the excitation and subsequent decay of the Δ -isobar via a $\Delta N \rightarrow NN$ reaction cannot be excluded. Though this reaction is suppressed for knockout of a proton pair in a $S = 0$, $T = 1$ state, a thorough investigation of the reaction mechanism is required before strong statements about the role of SRC can be made. Therefore, we have studied the $^{16}\text{O}(e, e'pp)^{14}\text{C}$ reaction at three values of the transferred energy ($\omega = 180, 210$ and 240 MeV), keeping the momentum transfer fixed at $q = 300$ MeV/ c . This implies that the invariant energy of the virtual photon and the two protons in the initial state gradually increases. Consequently, the contribution of intermediate Δ -excitation to the reaction will also increase with increasing energy transfer, which allows to experimentally estimate its size.

Nevertheless, to disentangle the contribution of the various processes contributing to the $(e, e'pp)$ reaction the data have to be compared to model predictions. In these models approximations are made. Exact many-body calculations starting from realistic NN interactions are, at this time, only feasible for $A \leq 7$ [7]. For more complex nuclei, the dynamics of nucleons at close proximity is incorporated in nuclear structure calculations by means of state-dependent correlation functions [8] or defect functions [9]. The experimental data, presented in this paper, are compared with the results of two calculations performed with the models of Ref. [5] and Ref. [10], respectively. Both models treat the dynamics of the the proton pair in the initial state, the medium effects of the Δ , and the final-state interaction of the ejectiles in a somewhat different way. By comparing the experimental cross sections with two independent calculations we aim at minimizing the model dependence in the interpretation of data.

The paper is organized as follows. In Section 2, some theoretical aspects and the kinematics of electron-induced two-nucleon knockout reactions are discussed. In Section 3, the experiments are briefly described, and the data are presented and compared to the results of theoretical calculations. Finally, conclusions are drawn and an outlook is given in Section 4.

2. Electron-induced two-nucleon knockout

The missing energy (E_m) and the missing momentum (\mathbf{p}_m) for the $(e, e'NN)$ reaction are defined as:

$$E_m = \omega - T'_1 - T'_2 - T_{A-2} \quad (1)$$

$$\mathbf{p}_m = \mathbf{q} - \mathbf{p}'_1 - \mathbf{p}'_2 \quad (2)$$

where $T'_{1,2}$ ($\mathbf{p}'_{1,2}$) and T_{A-2} (\mathbf{p}'_{A-2}) are the kinetic energies (momenta) of the knocked-out nucleons and the $A-2$ nucleus. The excitation energy of the $A-2$ nucleus is given by $E_x = E_m - S_{NN}$, where S_{NN} is the two-nucleon separation energy. Furthermore, the missing momentum \mathbf{p}_m is equal to the momentum of the recoiling nucleus \mathbf{p}_{A-2} . In a quasi-free knockout process, where the $A-2$ nucleus acts as spectator, \mathbf{p}_{A-2} is equal in size and opposite in direction to the momentum of the nucleon pair in the initial state: $\mathbf{p}_m = \mathbf{p}_{A-2} = -\mathbf{P}$. Hence, in quasi-free two-nucleon knockout, discarding the interactions in the final state, the cross section as a function of p_m reflects the centre-of-mass motion of the pair in the initial state. This motion is characterized by an angular momentum \mathbf{L} . Contrary to single-nucleon knockout from a target nucleus with $J = 0$, this angular momentum is not uniquely determined for a transition to a selected state in the residual nucleus; the total angular momentum of the two protons in the initial state $\mathbf{J} = \mathbf{j}_1 + \mathbf{j}_2$ can generally be composed in more than one way from the angular momenta associated with the relative motion \mathbf{l} and the center of mass motion of the pair \mathbf{L} , i.e. $\mathbf{J} = \mathbf{l} + \mathbf{L} + \mathbf{S}$. Nevertheless, the cross section as a function of p_m already contains valuable information on the reaction, as is discussed in Section 3.

More interesting information on the processes contributing to the knockout reaction is contained in the distribution of the cross section as a function of

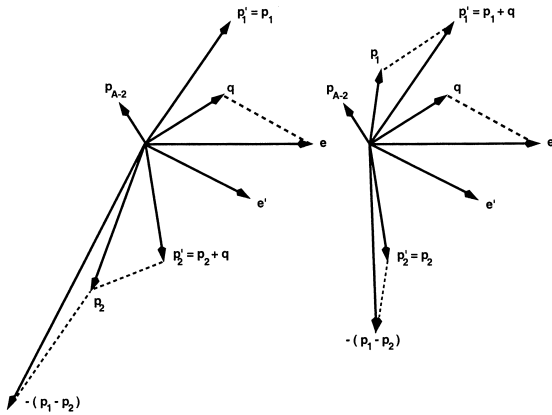


Fig. 1. Examples of the momentum transfer in an $(e, e' pp)$ reaction; in the left figure q is transferred to p_2 , the proton emitted in the backward direction, and in the right figure to p_1 , the proton that is emitted in the forward direction.

the relative momentum of the nucleons in the initial state, which is defined as $p = \frac{1}{2}(p_1 - p_2)$; p_1 and p_2 are the nucleon momenta in the initial state. The part of the cross section stemming from SRC is directly related to this momentum. This is illustrated in a simple factorization approximation of the cross section [1,11,12]. Assuming quasi-free knockout of two protons, the cross section can be approximated by:

$$\frac{d^3\sigma}{dV} = K \sigma_{epp}(p) F(E, P) \quad (3)$$

with $dV = dE_e d\Omega_e dE_{p_1} d\Omega_{p_1} dE_{p_2} d\Omega_{p_2}$. In this expression $F(E, P)$ represents the probability of finding a proton pair in the target nucleus, with energy E and center of mass momentum $P = p_1 + p_2$, and K is a kinematical factor. The dynamics of the knockout process is contained in $\sigma_{epp}(p)$, which accounts for the probability that the virtual photon is absorbed by a proton pair with relative momentum p . Unfortunately, the cross section as a function of p cannot be determined unambiguously from the measured proton momenta, because q can either be transferred to one of the nucleons, or shared by both. The former preferably occurs when the reaction is driven by SRC. If the reaction proceeds by meson exchange (MEC) or by excitation of the Δ -isobar, q is shared by both nucleons. For example, if the virtual photon is absorbed by the proton emitted in the forward

direction, the momenta of both protons in the final state are $p'_1 = p_1 + q$ and $p'_2 = p_2$, respectively.

By exchanging the indices 1 and 2 one obtains the momenta in the final state for a reaction, in which q is transferred to the proton that is emitted in the backward direction. Fig. 1 shows that, for given values of ω and q , the relative momenta of the two protons in the initial state are much larger in the second case than in the first one. Reversibly, the initial momenta p_1 and p_2 can be deduced from the measured ones p'_1 and p'_2 only if assumptions about the momentum transfer are made. Note that the relative momentum in the initial state probed in the $(e, e' NN)$ reaction increases at increasing value of ω (cf. Fig. 2). Moreover, the range for $|p|$ covered in an $(e, e' pp)$ experiment depends on the ranges in p'_1 and p'_2 spanned by the proton detectors. Assuming $P = 0$, and taking constant values of ω and $|q|$, the relative momenta in the initial state probed in the reaction increase at increasing value of γ_1 , i.e. the angle of p'_1 with respect to $|q|$.

Theoretically, the dependence of the cross section on the momenta of the nucleons in the initial state is expressed in the transition matrix elements for the nuclear charge-current density operators. The one-body part of this operator describes the coupling of the virtual photon to either of the two nucleons. In the Pavia-model [5], the two-proton transition ampli-

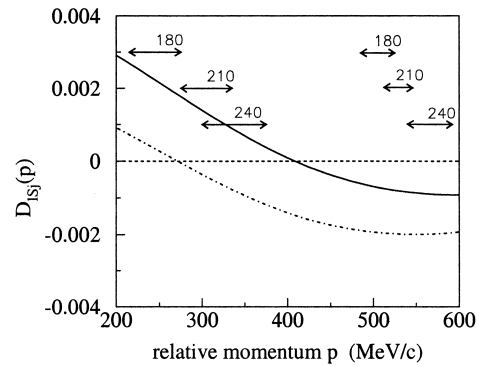


Fig. 2. The solid curve shows the defect function for a 1S_0 proton pair in ^{16}O according to Ref. [9], whereas the dot-dashed curve is obtained from a Fourier transform of the correlation function of Ref. [14]. The arrows indicate the ranges in relative momenta, probed at the three values of the transferred energy. Details are given in the text.

tude, linking the initial state to a specific final state, is obtained through the calculation of the spectral density function in a harmonic oscillator basis, and within a large configuration space [9]. This wave function is converted to wave functions for the center-of-mass motion and the relative motion of the pair. SRC are implemented by adding the defect functions $D_{\text{ISj}}(r)$ [13] to the wave functions of the relative motion, according to:

$$\Psi_{\text{nlSj}}(r) = \Phi_{\text{nl}}(r) + D_{\text{ISj}}(r) \quad (4)$$

where r is the inter-nucleon distance, and $\Phi_{\text{nl}}(r)$ are harmonic oscillator wave functions.

These defect functions depend only on the quantum state of the relative motion. SRC are strongest for a pair in a 1S_0 state. In Fig. 2, the defect function for a proton pair in a 1S_0 state calculated with the Bonn-A potential is shown for a relative momentum p in the range 200–600 MeV/ c . This defect function and the one for the 3P_1 state are used for the calculations presented here.

In the Gent-model [10] single-particle wave functions obtained from Hartree–Fock calculations are used. Therefore, no formal separation into relative and center-of-mass coordinates can be made. In this model the many-body wave function, approximated to first order in the correlation function, is expressed as:

$$\Psi(\mathbf{r}_1, \dots, \mathbf{r}_A) = \prod_{i < j=1}^A (1 - g(r_{ij})) \Phi(\mathbf{r}_1, \dots, \mathbf{r}_A) / \sqrt{N}. \quad (5)$$

SRC are contained in the factor $(1 - g(r_{ij}))$. In the absence of correlations $g(r_{ij})$ is zero. N is a normalisation factor. The results presented in this paper are obtained using the correlation function $g(r_{ij})$ of Ref. [14]. Fig. 2 shows the defect function obtained by performing a Fourier transform of this correlation function.

In both calculations, the excitation of the Δ -resonance and its subsequent decay by exchange of a pion, which is the dominant process contributing to the two-body hadronic currents, is derived from an effective Lagrangian. Medium effects of the Δ -isobar are, however, included in a different way. This also holds for the distortion effects in the final state. In the Pavia-model, the interaction of the outgoing

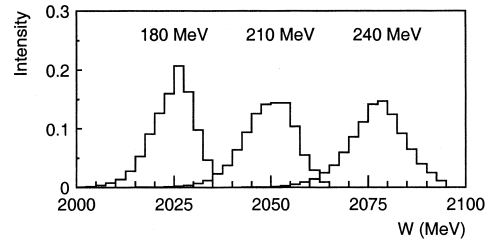


Fig. 3. Distribution of the invariant energy $W_{p'_1 p'_2}$ for the central values of the transferred energy.

particles with the residual nucleus is accounted for by means of an optical potential for each of the outgoing nucleons, whereas in the Gent-model an A -body wave function for the two ejectiles and the residual nucleus in a two-hole state is obtained by a partial wave expansion in terms of the $2p - 2h$ eigenstates of a mean-field Hamiltonian.

As mentioned before, information on the mechanism of the $(e, e'pp)$ reaction can be obtained by measuring the differential cross section at various values of the transferred energy and momentum. In particular, the contribution to the cross section of the excitation of the Δ -isobar and its subsequent decay via a $\Delta N \rightarrow NN$ reaction strongly depends on the invariant energy of the virtual photon and the two protons in the initial state $W_{\gamma p_1 p_2}$. In a quasi-free knockout reaction this quantity is equal to the invariant energy of the two ejectiles $W_{p'_1 p'_2}$. In Fig. 3 the distribution of $W_{p'_1 p'_2}$, calculated within the detection volume for the transition to the ground state, is depicted for the three values of ω . This figure illustrates that the differences in $W_{p'_1 p'_2}$ are sufficient to expect a systematic increase of the strength of the two-body currents in the three measurements. Furthermore, the invariant energy corresponding to the largest value of ω is still well below the mass of the ΔN system, which is 2170 MeV/ c^2 .

3. The reaction $^{16}\text{O}(e, e'pp)^{14}\text{C}_{\text{gs}}$

The experiments were performed with electrons extracted from the Amsterdam Pulse Stretcher (AmPS). The energy of the incident electrons was in the range 580–585 MeV, and the average beam current in the range 2–3 μA , with a macroscopic

duty factor of approximately 70%. A waterfall target, with a thickness of 210 mg/cm² was used [15]. The scattered electrons were detected in a magnetic spectrometer of the QDQ type, and the knocked-out protons in two plastic scintillator arrays, HADRON3 and HADRON4 [16]. In the forward hemisphere, protons were detected at angles in the range $3^\circ \leq \gamma_1 \leq 42^\circ$, and in the backward direction at angles in the range $-114^\circ \geq \gamma_2 \geq -173^\circ$. The detection volume, determined by these angular ranges and the energy acceptances of the HADRON detectors, includes for the transition to the ground state p_m values as low as 50 MeV/c at $\omega = 180$ MeV, and 25 MeV/c at $\omega = 240$ MeV. Details of the experiments and the data analysis can be found in Ref. [17]. In Fig. 4 the low energy part of the excitation-energy spectrum ($E_x \leq 10$ MeV), measured for $\omega = 180$ MeV, is shown. This spectrum includes the transitions to the ground state and the two lowest 2^+ states of ^{14}C . The strength in the range $-4 \leq E_x \leq 4$ MeV can be almost exclusively attributed to the ground-state transition. The average background in this region, determined from the yield in the range $-100 \leq E_x \leq -10$ MeV is $(4 \pm 6 \%)$ of the peak intensity. Due to the achieved energy resolution of 4.5 MeV

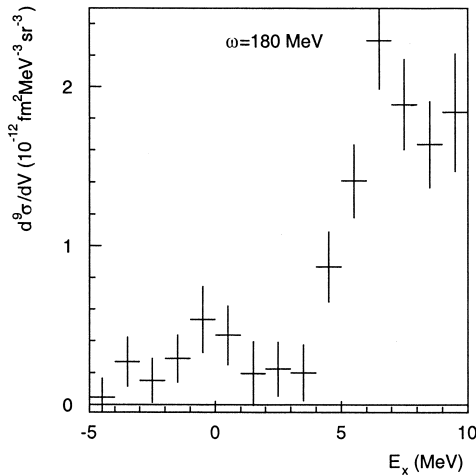


Fig. 4. Excitation-energy spectrum measured for the reaction $^{16}\text{O}(e,e'pp)^{14}\text{C}$. The cross section in the range $-4 \leq E_x \leq 4$ MeV can be almost exclusively attributed to the ground-state transition.

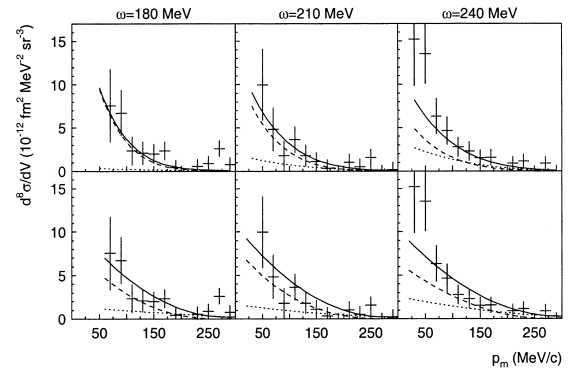


Fig. 5. The cross sections for the transition to the ground state in ^{14}C ($-4 \leq E_x \leq 4$ MeV) as a function of the missing momentum, measured for the reaction $^{16}\text{O}(e,e'pp)^{14}\text{C}$ at three values of ω . The curves are obtained from calculations with the Pavia-model (top) and Gent-model (bottom). The solid curves represent the calculated cross sections; the dashed and dotted curves correspond to the contributions of the one- and two-body hadronic currents, respectively.

(FWHM), the contribution of the first 2^+ to the ground-state is $\leq 5\%$. This contribution has been deduced from a fit of three Gaussian functions, corresponding to the transitions to the ground state and the two 2^+ states at excitation energies of 7.0 and 8.3 MeV, to the data.

Fig. 5 shows the cross sections as a function of the missing momentum for the interval $-4 \leq E_x \leq 4$ MeV at the three values of ω . In Section 2, it is argued that the angular momenta of the two protons can couple to the angular momentum for the relative and the center-of-mass motion in various ways. The scheme for coupling a $(p_{1/2})^2$ or $(p_{3/2})^2$ proton-pair to total angular momentum $J=0$, leaving the ^{14}C nucleus in the ground state, is as follows. The two protons can be either in a 1S_0 or in a 3P_1 state. With a 1S_0 state always $L=0$ for the angular momentum of the center-of-mass motion is associated, and with a 3P_1 state always $L=1$. From Fig. 5 it is clear that for all three values of ω the missing-momentum dependence of the measured cross sections is similar. In Ref. [1,4] it has been pointed out that such a momentum distribution reflects an angular momentum $L=0$ for the center-of-mass motion of the pair, and thus suggests a dominant role for the knockout of a 1S_0 pair driven by SRC. Two-body hadronic

currents (intermediate Δ -excitation) contribute mainly to the 3P_1 wave [4,5].

A prominent role of two-step processes in the $(e, e'pp)$ reaction, including an $(e, e'pn)$ reaction followed by a charge exchange (pn, pp) reaction, can be excluded. A calculation performed within the Lane model [18], implying charge exchange between isobaric analog states shows that the contribution due to the absorption of a virtual photon by a pn pair in $S=0, T=1$ state, followed by a charge exchange (n, p) reaction is small. The other contribution stems from charge exchange after absorption of the virtual photon by a $S=1, T=0$ pn pair. The strength for the first step in this process is predicted to be about a factor 5–10 larger than that for knockout of a $S=0, T=1$ pair. However, in this case the second step is a spin-flip transition. The cross section for such transition is known to be much smaller than that for a transition between analog states. Hence, also this process is not expected to contribute strongly to the $(e, e'pp)$ reaction. These theoretical predictions are confirmed by the ratios for the (γ, pp) and (γ, pn) cross sections at small missing energy, measured for absorption of real photons by the nucleus ^{12}C [19]. These ratios vary strongly with the proton emission angle. A strong feeding of the $^{12}\text{C}(\gamma, pn)$ reaction to the $^{12}\text{C}(\gamma, pp)$ reaction, for which the measured cross section is about a factor six smaller than that for the $(e, e'pn)$ reaction, would result in comparable angular distributions for both reactions. This has led to the conclusion that both reactions likely proceed via different mechanisms.

This qualitative interpretation of the data is supported by the results of the microscopic calculations performed with the models developed by the Pavia group [5] and Gent group [10], which are also shown in Fig. 5. In these calculations, the transition matrix elements contain contributions from one-body and two-body hadronic currents. The two-proton overlap amplitudes for the transition $^{16}\text{O} \rightarrow ^{14}\text{C}_{\text{gs}}$, used in the Pavia-model, are taken from DRPA (Dressed-Random-Phase-Approximation) calculations, performed within a large configuration space [9]. In the calculations performed with the Gent-model the “two-nucleon coefficients of fractional parentage” (cf.p.) of Cohen and Kurath [20] are used. These coefficients are renormalised by a factor 0.85^2 to account for the depletion of the calculated spectro-

scopic strength in the $1p_{1/2}$ shell due to long-range correlations, according to Ref. [9]. This means that the spectral amplitude for knockout of two protons from the $1p_{1/2}$ shell is equal in both calculations, but that the amplitude for knockout of a $1(p_{3/2})^2$ pair is a factor 1.8 larger in the calculations with the Gent-model than in those performed with the Pavia-model. However, this difference has only a small effect on the cross section for knockout of a 1S_0 pair with angular momentum $L=0$ for the centre-of-mass motion, because this cross section is largely determined by knockout of a proton pair from the $1p_{1/2}$ shell.

The theoretical cross sections are represented in Fig. 5 by the solid curves; the contributions of the one- and two-body currents are given by the dashed and dotted curves, respectively. The calculated cross sections agree well with the data at all three values of ω . The curves, representing the contributions of the one- and two-body currents to the ground-state transition, indicate that at $\omega = 180$ and 210 MeV the reaction is dominated by one-body currents, and that the contribution of two-body currents increases with increasing energy transfer. Conceptually both models are quite similar, and neither of the two contains free parameters. As discussed in Section 2, SRC are accounted for in a different way, e.g. by defect functions in the Pavia-model and a correlation function in the Gent-model. The Bonn-A and Reid Soft Core potentials, adopted in the calculations, are both realistic NN-potentials and successfully used in many nuclear-structure calculations. Hence, the data agree with the theoretical results obtained independently with the two models. Furthermore, both models predict that the largest contribution to the cross section stems from one-body hadronic currents driven by SRC. This justifies the conclusion that evidence is obtained for SRC.

Note that the experimental as well as the theoretical cross sections are rather constant as a function of ω . Apparently the increase of the two-body currents, due to intermediate Δ -excitation, is compensated by a decrease of the one-body currents. As pointed out in Section 2, the contribution of the two-body currents to the cross section, originating from the excitation and subsequent decay of the Δ -isobar, increases with the invariant energy $W_{p_1 p_2}$. The observed differences between the theoretical predictions are likely

due to the assumptions with respect to the Δ -propagators. The Gent-model accounts explicitly for medium effects in the Δ -propagator. Therefore, the peak of the Δ -resonance appears at a slightly lower energy, and its width is somewhat larger in this model than in the Pavia-model. This explains the larger contribution of the two-body currents in the calculations performed with the Gent-model at the lowest value of ω .

Though the relative momenta involved in the knock-out process cannot be determined unambiguously from the data, the defect functions shown in Fig. 2 determine the ranges in relative momentum probed in the reaction and the dependence of the cross sections on the transferred energy. For example, in the calculations performed with the Pavia-model the strength generated by the one-body currents decreases with increasing ω . This is due to decrease of the defect function with an increasing relative momentum of the protons in the initial state in the domain $200 \leq p \leq 400$ MeV/ c . The increase of the relative momentum probed in the $(e, e'pp)$ reaction at increasing ω is a kinematic effect, discussed in Section 2. Furthermore, the defect function for the Bonn-A potential, displayed in Fig. 2 is, within the phase space of this experiment, largest for $\omega = 180$ and 210 MeV when q is transferred to p_1 (cf. Fig. 1). In this case, the ranges in relative momenta spanned are 220–270 MeV/ c and 270–330 MeV/ c , respectively. When q is transferred to p_2 , these relative momenta are 480–525 MeV/ c ($\omega = 180$ MeV) and 515–540 MeV/ c ($\omega = 210$ MeV). Hence, for these values of the transferred energy, the transition amplitude is largest when the virtual photon is absorbed by the proton that is emitted in the forward direction. At $\omega = 240$ MeV, the contributions of both possible absorption processes to the one-body currents, including relative momenta in the ranges 300–360 MeV/ c and 540–590 MeV/ c , respectively, are comparable in size. The situation is different for the calculations performed with the Gent-model. The correlation function adopted in this model is of shorter range than the defect function used in the Pavia-model. Correspondingly, the absolute value of the defect function is largest in the domain of relative momenta 400–600 MeV/ c (cf. Fig. 2). This implies that the contribution to the cross section stemming from the transfer of the virtual

photon to the proton that is emitted in the backward direction is the largest one at all three values of ω . Hence, the momentum dependence of the employed defect/correlation function indicates that the contribution of SRC to the cross section in the Gent-model is dominated by relative momenta in the range 480–600 MeV/ c , whereas the Pavia-model predicts that the cross section is largely determined by relative momenta in the range 220–370 MeV/ c . Though the presented data nicely illustrate the potential of the $(e, e'pp)$ reaction to probe specific ranges of relative momenta, no formal discrimination between the results of both calculations can be made yet, and neither the defect function obtained with the Bonn-A potential nor the correlation function calculated with the Reid Soft Core potential can be excluded. Measurements at complementary values of (ω, q) , thus probing other domains of relative momenta, could resolve the observed ambiguity. Furthermore, a more consistent description of the dynamics of nucleons in the nuclear medium at small inter-nucleon distances could reduce the uncertainties in the theoretical results.

4. Conclusions and outlook

The reaction $^{16}\text{O}(e, e'pp)^{14}\text{C}_{\text{gs}}$ has been studied at three values of the transferred energy. The dependences of the cross sections on the missing momenta reflect the characteristic features for knockout of two protons with an angular momentum of the center-of-mass motion $L = 0$. The cross sections are well reproduced by the results of two independent calculations. Both calculations predict a relatively small contribution from intermediate Δ -resonance excitation to the cross section; the major part is due to SRC. In that respect we are confident to claim direct evidence for SRC in the nucleus ^{16}O .

Within the phase space covered by the experiment, relative momenta between the two protons in the initial state in the range 220–600 MeV/ c are involved. The data do not allow to determine which relative momenta predominantly contribute to the cross sections measured at the three values of ω . They can be either in the range 220–370 MeV/ c or in the range 480–600 MeV/ c , depending on the coupling of the virtual photon to either of the two

ejectiles. Also the calculations cannot discriminate between those two possibilities. Due to the differences in both models with respect to the short-range part of the relative wave function of the proton-pairs in the initial state, both models give different predictions with respect to relative momenta that predominantly determine the cross sections. An improved description of the nuclear structure and a more detailed study of the final state interaction may provide insight in this intriguing ambiguity. In addition, a study of the q dependence of the cross section may shed light on this issue, because the relative momenta in the initial state, probed experimentally, depend on q and ω in a different way.

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